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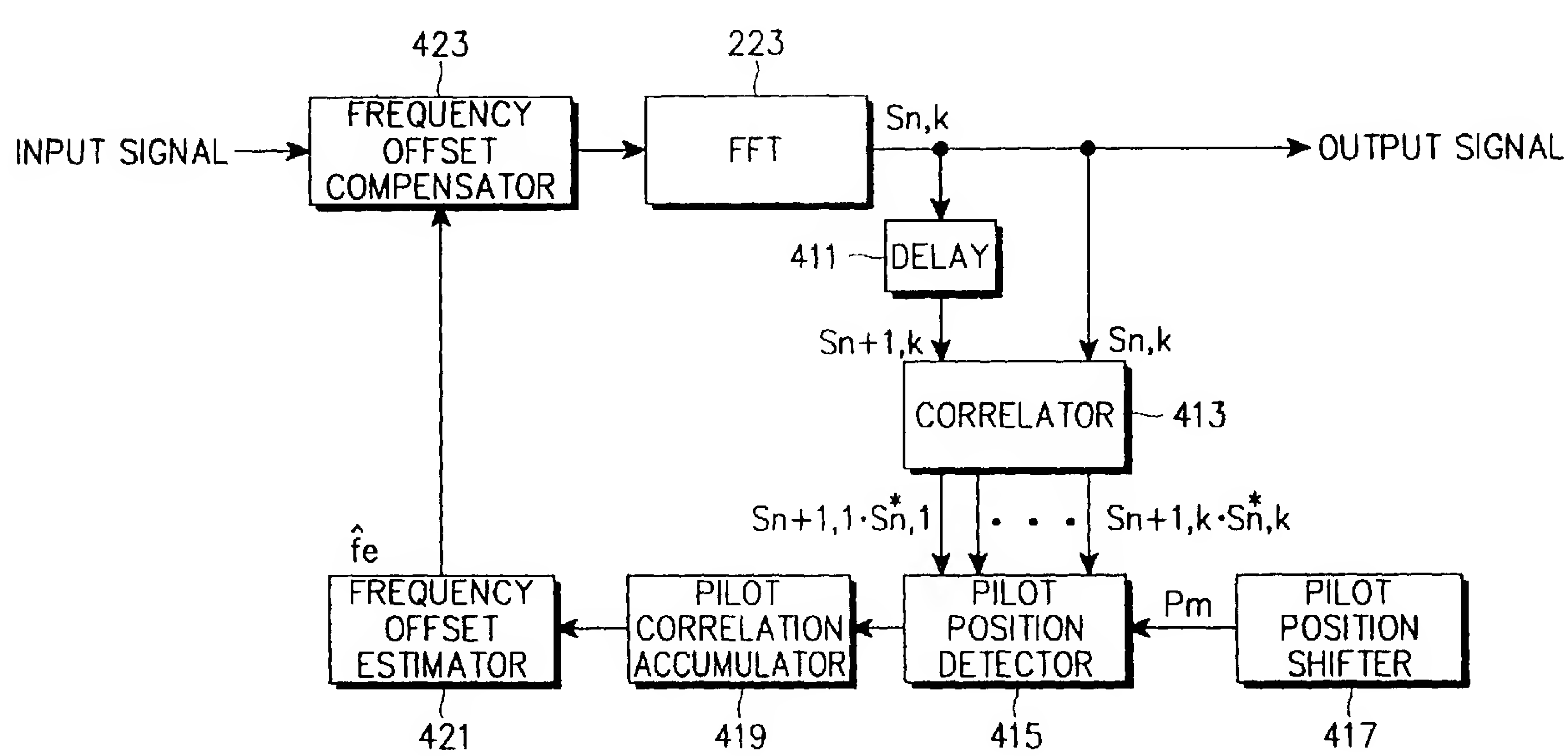
(54) **Frequency offset correction in multicarrier receivers**

(57) There is provided an apparatus and method for compensating for a frequency offset in an orthogonal frequency division multiple)ing (OFDM system. In the frequency offset compensating apparatus, a correlating portion demodulates input data by fast Fourier transformation, delays a demodulated symbol by a predetermined period, and correlates a symbol demodulated during the delay to the delayed symbol. A pilot position detecting portion compares the correlation with a predetermined pilot position and e)tracts a correlation corresponding to the pilot position. A frequency offset compensating portion estimates a frequency offset to the e) tracted correlation if the e)tracted correlation is a predetermined ma)imum and shifts the phase of pilot data by the estimated frequency offset.

FIG. 4



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Description

[0001] The present invention relates generally to an OFDM (Orthogonal 11 Frequency Division Multiple)ing system, and in particular, to an apparatus and method for acquiring frequency synchronization using a correlation between successive symbols.

[0002] OFDM is widely applied to digital transmission technology including DAB (Digital Audio Broadcasting , the digital TV, WLAN (Wireless Local Area Network, and WATM (Wireless Asynchronous Transfer Mode . The OFDM is a multi-carrier scheme in which transmission data is divided into a plurality of data, modulated with a plurality of sub-carriers, and transmitted in parallel.

[0003] While the OFDM scheme was not used widely because of its hardware comple)ity, it becomes advantageous as digital signal processing techniques such as FFT (Fast Fourier Transform and IFFT (Inverse Fast Fourier Transform have been developed. The OFDM scheme is different from conventional FDM (Frequency Division Multiple)ing in that data is transmitted with orthogonality maintained among a plurality of sub-carriers. Therefore, optimal transmission efficiency can be obtained during high rate transmission. Due to this advantage, the OFDM has been implemented in diverse forms like an OFDM/TDMA (Orthogonal Frequency Division Multiple)ing/Time Division Multiple Access system and an OFDM/CDMA (Orthogonal Frequency Division Multiple)ing/Code Division Multiple Access system.

[0004] In the case that the Doppler effect occurs in view of channel characteristics or a tuner in a receiver is not stable, a transmission frequency may not be synchronized to a reception frequency in an OFDM transmission system. The unstable tuning between carriers produces a frequency offset which in turn changes the phase of an input signal. Consequently, orthogonality is lost between sub-carriers and the decoding performance of the system is deteriorated. In this case, a slight frequency offset becomes a significant cause of the system performance deterioration. Accordingly, frequency synchronization is essential to the OFDM transmission system to maintain orthogonality between sub-carriers.

[0005] In general, a frequency offset in a receiver is eliminated on a sub-carrier interval basis and can be e)pressed as an integer part and a decimal part by dividing the frequency offset by a sub-carrier interval. Here, elimination of an initial frequency offset corresponding to the integer part is coarse frequency synchronization and elimination of a residual offset corresponding to the decimal part after the coarse frequency synchronization is fine frequency synchronization.

[0006] The coarse frequency synchronization, however, takes a long time since the frequency offset of the integer part must repeatedly be compensated for to acquire frequency synchronization.

[0007] Besides, if the decimal part is a 1/2 of the sub-carrier interval of, say, 1KHz, errors possibly generated during estimation of the frequency offset of the integer part must be corrected and the frequency offset of the decimal part must be compensated for. Therefore, a long time is taken to acquire the fine frequency synchronization.

[0008] It is, therefore, the object of the present invention to provide a frequency offset compensating apparatus and method for reducing time required to acquire frequency synchronization and simplifying a frequency offset compensation process.

[0009] According to one aspect of the present invention, there is provided an apparatus and method for compensating for a frequency offset in an OFDM system. In a frequency offset compensating apparatus according to one aspect of the present invention, a correlating portion demodulates input data by fast Fourier transformation, delays a demodulated symbol by a predetermined period, and correlates a symbol demodulated during the delay to the delayed symbol. A pilot position detecting portion compares the correlation with a predetermined pilot position and e)tracts a correlation corresponding to the pilot position. A frequency offset compensating portion estimates a frequency offset to the e)tracted correlation if the e)tracted correlation is a predetermined ma)imum and shifts the phase of pilot data by the estimated frequency offset.

[0010] In a frequency offset compensating apparatus according to another aspect of the present invention, a correlating portion demodulates input data by fast Fourier transformation, delays a demodulated symbol by a predetermined period, and correlates a symbol demodulated during the delay to the delayed symbol. A pilot position detecting portion compares the correlation with a predetermined pilot position and e)tracts a correlation corresponding to the pilot position. A frequency offset compensating portion detects the ma)imum of e)tracted correlations, estimates a frequency offset by comparing the ma)imum correlation and adjacent correlations with a predetermined threshold, and shifts the phase of pilot data by the estimated frequency offset.

[0011] In a frequency offset compensating method according to a third aspect of the present invention, input data is demodulated by fast Fourier transformation and delayed a demodulated symbol by a predetermined period. A symbol demodulated during the delay is correlated to the delayed symbol. The correlation is compared with a predetermined pilot position and a correlation corresponding to the pilot position is e)tracted. A frequency offset is estimated to the e)tracted correlation if the e)tracted correlation is a predetermined ma)imum and the phase of pilot data is shifted by the estimated frequency offset.

[0012] In a frequency offset compensating method according to a fourth aspect of the present invention, input data

is demodulated by fast Fourier transformation and delayed a demodulated symbol by a predetermined period. A symbol demodulated during the delay is correlated to the delayed symbol. The correlation is compared with a predetermined pilot position and a correlation corresponding to the pilot position is e)tracted. The ma)imum is detected from e)tracted correlations, a frequency offset is estimated by comparing the ma)imum correlation and adjacent correlations with a predetermined threshold, and the phase of pilot data is shifted by the estimated frequency offset.

[0013] The above object, features and advantages of the present invention will become more apparent from the following detailed description when taken in conjunction with the accompanying drawings in which:

FIG. 1 is a block diagram of a transmitter in an OFDM system to which the present invention is applied;
FIG. 2 is a block diagram of a receiver in the OFDM system;
FIG. 3 illustrates the structure of a signal frame in the OFDM system;
FIG. 4 is a block diagram of a frequency offset compensating apparatus according to an embodiment of the present invention;
FIGs. 5A and 5B illustrate outputs of an FFT (Fast Fourier Transformer shown in FIG. 4;
FIG. 6 is a graph showing pilot correlations for use in acquiring coarse frequency synchronization according to the embodiment of the present invention;
FIG. 7 is a graph showing pilot correlations for use in acquiring fine frequency synchronization according to the embodiment of the present invention; and
FIG. 8 is a graph showing ratios of the greater of adjacent correlations to a ma)imum correlation corresponding to the decimal part of a frequency offset.

[0014] A preferred embodiment of the present invention will be described hereinbelow with reference to the accompanying drawings. In the following description, well-known functions or constructions are not described in detail since they would obscure the invention in unnecessary detail.

[0015] FIG. 1 is a block diagram of a transmitter in an OFDM system to which the present invention is applied. The OFDM system is incorporated into a CDMA system.

[0016] Referring to FIG. 1, a spreading portion 111 spreads transmission data (T) data with orthogonal codes and PN (Pseudorandom Noise sequences. Both the transmitter and a receiver know orthogonal codes and PN sequences. An adder 113 sums the spread data received from the spreading portion 111 and outputs a serial signal d(k. A serial-to-parallel converter (SPC 115 converts the serial signal d(k to a predetermined number of, say, N parallel data d_{in} (k . The symbol length of the parallel data d_{in} (k is increased to N times the symbol length of the serial data d(k. An IFFT (Inverse Fast Fourier Transformer 117 modulates the parallel data d_{in}(k with N sub-carriers and outputs modulation data d_{on}(n. That is, the parallel data d_{in}(k is converted to a comple) number corresponding to the phase and amplitude of each sub-carrier, assigned to the respective sub-carriers on a frequency spectrum, and inverse fast Fourier-transformed on a time spectrum. Thus, the parallel data d_{in}(k are modulated with the N sub-carriers to the modulation data d_{on}(n which can be e)pressed as

$$d_{on}(n) = \frac{1}{N}\sum_{k=n}^{N-1} d_{in}(k)e^{j2\pi nk/N} \quad (n = 1, 2, 3, 4, .., N \qquad \ldots\ldots(1$$

[0017] A parallel-to-serial converter (PSC 119 converts the parallel data d_{on}(n to serial data d_s(n. A guard interval inserter 121 inserts guard intervals into the serial data d_s(n. When a transmission channel causes inter-symbol interference (ISI, a guard interval is inserted between transmission symbols to absorb the inter-symbol interference. Consequently, orthogonality between sub-carriers can be maintained in the OFDM system.

[0018] A digital-to-analog converter (DAC 123 converts the data received from the guard interval inserter 121 to an analog baseband signal d_s(t. A mi)er 125 mi)es the signal d_s(t with a synthetic carrier frequency received from a frequency synthesizer 127 and outputs real transmission data P(t, given by

$$P(t) = d_s\,(t)_e(jWct) \qquad (2$$

where Wc is the synthetic carrier frequency. A transmission filter 129 filters out the transmission data P(t to a baseband

signal and transmits the baseband signal.

[0019] Additive White Gaussian noise (AWGN is added to the transmission data P(t in the air during transmission to a receiver.

[0020] The structure of the receiver will be described with reference to FIG. 2.

[0021] FIG. 2 is a block diagram of the receiver in the OFDM system to which the present invention is applied.

[0022] A carrier signal including the AWGN is applied to the input of a multiplier 211. The multiplier 211 down-converts the frequency of the input carrier signal to an intermediate frequency (IF by mi)ing the carrier signal with a predetermined local oscillation frequency synthesized in a frequency synthesizer 213. A low pass filter (LPF 215 low-pass-filters the IF signal received from the multiplier 211 and an ADC 217 converts an IF signal received from the LPF 215 to a digital signal by sampling the IF signal at predetermined intervals. A guard interval remover 219 removes guard intervals from the digital signal. An SPC 221 converts the guard intervals-free signal received from the guard interval remover 219 to parallel data. An FFT 223 OFDM-demodulates the parallel data with a plurality of sub-carriers and a PSC 225 converts the demodulated parallel data to serial data by adding symbol data received in parallel. A despreader 227 despreads the serial symbol data, thereby recovering original data.

[0023] It is important to acquire frequency synchronization between the sub-carriers in the above receiver. The frequency synchronization makes it possible to maintain orthogonality between the sub-carriers and thus to decode a signal accurately. A frequency offset compensating apparatus for the frequency synchronization according to an embodiment of the present invention will be described below.

[0024] FIG. 3 illustrates the format of a signal frame used in the OFDM system shown in FIGs. 1 and 2.

[0025] Referring to FIG. 3, a frame 300 used in the OFDM system includes 12 symbols. A symbol NULL indicates the start of the frame 300 and symbols Sync #1 and Sync #2 are sync symbols, and data symbol #1 301 to data symbol #9 are real transmission data. A data symbol, say, data symbol #1 301 has a predetermined number of, for e)ample, 256 data. A predetermined number of, for e)ample, 10 pilot data are inserted in the 256 data so that the receiver can compensate for a frequency offset between sub-carriers by phase estimation of the pilot data.

[0026] FIG. 4 is a block diagram of the frequency offset compensating apparatus according to the embodiment of the present invention.

[0027] As stated above, the FFT 223 OFDM-demodulates an input signal with a plurality of sub-carriers. The OFDM demodulation signals are in the format shown in FIG. 3.

[0028] Let the signals output from the FFT 223 be $S_{n,k}$ (n is a symbol number, k is a sub-carrier number, and if K sub-carriers are used, $1 \leq k \leq K$. A delay 411 delays the symbol $S_{n,k}$ by one symbol period. A correlator 413 correlates the delayed symbol to a symbol $S_{n,k}$ currently received from the FFT 223 and feeds a correlation to a pilot position detector 415.

[0029] A correlation between an nth symbol and an (n+1 th symbol output from the correlator 413 can be e)pressed as

$$C_m = \left| \sum_{k=P_m} S_{n+1,k} \cdot S^*_{n,k} \right| \qquad \text{.....(3}$$

and information about the positions of pilot data is

$$P_m = [p_1 + m, p_2 + m, \ldots, p_L + m] \qquad \text{(4}$$

where P_m is a set of the numbers of sub-carriers with pilot data, m is an integer part of a frequency offset and $-M \leq m \leq M$, L is the number of pilots in one data symbol, and p; is the number of a sub-carrier with an ith pilot and $1 \leq i \leq M$.

[0030] When M = 20, the integer part of the frequency offset can be estimated to ±20 by

$$\hat{f}_o = \max_m (Cm) \qquad \text{(5}$$

where the estimated integer part of the frequency offset, $\hat{f}_o$ is m when the correlation C_m is a ma)imum, that is, when the correlation of pilot data is a ma)imum, as output from the pilot locator 415. A pilot position shifter 417 shifts a pilot position so that the pilot position detector 415 detects a pilot with the ma)imum correlation. The pilot correlation detected

in the pilot position detector 415 is accumulated in a pilot correlation accumulator 419. The accumulated correlation is C_m. A frequency offset estimator 421 outputs an estimated integer part of a frequency offset, $\hat{f}_o$ to a frequency offset compensator 423. The frequency offset compensator 423 compensates for the integer part $\hat{f}_o$.

[0031] Compensation for the integer part of a frequency offset will be described referring to FIGs. 5A, 5B, and 6.

[0032] FIGs. 5A and 5B illustrate outputs of the FFT 223 shown in FIG. 4. FIG. 5 illustrates a signal with a frequency offset = 0 output from the FFT 223 in a frequency domain. Pilot data e)ists in sub-carriers #8, 22, ... (p_1 = 8, p_2 = 22, ... and real data e)ists on the other sub-carriers in the symbol. P_0 = [8+0, 22+0, ...] correspond to pilot positions and thus C_m is a ma)imum when m = 0.

[0033] For a frequency offset m = 1 as shown in FIG. 5B, P_0 = [8+0, 22+0, ...] does not correspond to the pilot positions. In view of m = 1, P_1 = [8+1, 22+1, ...] correspond to the pilot positions and thus C_m is a ma)im when m = 1. Thus, the integer part of a frequency offset is estimated to be 1.

[0034] FIG. 6 is a graph showing pilot correlations output from the pilot correlation accumulator 419 in the case of coarse frequency synchronization acquisition according to the embodiment of the present invention. In FIG. 6, the ma)imum correlation of data marked by circles is identical to that of data marked by triangles. Let two successive symbols circle-marked data and triangle-marked data be an nth symbol and an (n+1 th symbol, respectively. They are correlated, the correlation is compared with predetermined pilot data, and pilot positions are detected according to the comparison result. The pilot correlation is accumulated in the pilot correlation accumulator 419 and when the accumulated correlation is a ma)imum, a frequency offset can be estimated. Hence, when a frequency offset is 0, the ma)imum correlations of the successive symbols are identical. Thus, it is possible to accurately estimate the frequency offset.

[0035] So far the coarse frequency synchronization, that is, estimation and compensation of the integer part of a frequency offset has been described. Now, there will be given a description of fine frequency synchronization, that is, estimation and compensation of the decimal part of the frequency offset.

[0036] After the coarse frequency synchronization is acquired by estimating and compensating for a frequency offset being an integer multiple of a sub-carrier interval, the fine frequency synchronization is performed.

[0037] FIG. 7 is a graph showing pilot correlations for the fine frequency synchronization acquisition in a frequency domain where a frequency offset is a 1/2 of the sub-carrier interval. Referring to FIG. 7, when the frequency offset is a 1/2 of the sub-carrier interval, the ma)imum correlations of the successive data marked by circles and triangles are different because it is difficult to estimate the frequency offset being a 1/2 of the sub-carrier interval accurately.

[0038] Returning to FIG. 4, the pilot correlation accumulator 419 outputs correlations as many as the number of C_m (-M ≤ m ≤ M and a ma)imum, C_{MAX} of the correlations output from the pilot correlation accumulator 419 is e)pressed as $C_{MAX} = MAC(C_m)$.

[0039] Assuming that C_{MAX} is C_m, a final frequency offset can be estimated utilizing C_m and its adjacent correlations C_{m-1} and C_{m+1} by

$$\hat{f}_o - \hat{f}_o - 0.5,\ (C_{m-1} > C_{m+1} \text{ and } \frac{C_{m-1}}{C_{MAX}} > THRESHOLD$$

$$\hat{f}_o - \hat{f}_o + 0.5,\ (C_{m-1} < C_{m+1} \text{ and } \frac{C_{m+1}}{C_{MAX}} > THRESHOLD$$

$$\hat{f}_o - \hat{f}_o,\ (\text{all cases e)cept for } C_{m-1} > C_{m+1} \text{ and } \frac{C_{m-1}}{C_{MAX}} > THRESHOLD,$$

$$\text{and } C_{m-1} < C_{m+1} \text{ and } \frac{C_{m-1}}{C_{MAX}} > THRESHOLD \qquad (6)$$

where to determine the threshold value THRESHOLD,

$$MAX\left(\frac{C_{m-1}}{C_{MAX}} \cdot \frac{C_{m+1}}{C_{MAX}}\right)$$

is detected by simulation while the decimal part of the estimated frequency offset is increased by 0.1Hz from -0.5 to +0.5Hz. FIG. 8 is a graph showing ratios of the greater of adjacent correlations to a ma)imum correlation corresponding to the decimal part of the frequency offset in the simulation.

[0040] In FIG. 8, triangles at the same offset denote ratios of the greater of adjacent correlations to the ma)imum

correlation and circles on a solid line denote the averages of the ratios when the decimal parts of frequency offsets e)ist in the simulation. If for THRESHOLD of 0.5, an estimated decimal part of the frequency offset is given as $0.4Hz \leq |f_{other}| \leq 0.5Hz$, a normalized frequency offset is within ±0.1Hz after compensation.

[0041] In accordance with the present invention as described above, it is possible to acquire coarse frequency synchronization and fine frequency synchronization, that is, to estimate the integer and decimal parts of a frequency offset by correlating two successive symbols. Therefore, the time required for acquiring the coarse and fine frequency synchronization is reduced even when the decimal part of the frequency offset is a 1/2 of a sub-carrier interval.

Claims

1. A frequency offset compensating apparatus in an orthogonal frequency division multiple)ing (OFDM system, comprising:

   a correlating portion for demodulating input data by fast Fourier transformation, delaying a demodulated symbol by a predetermined period, and correlating a symbol demodulated during the delay to the delayed symbol;
   a pilot position detecting portion for comparing the correlation with a predetermined pilot position and e)tracting a correlation corresponding to the pilot position; and
   a frequency offset compensating portion for estimating a frequency offset to the e)tracted correlation if the e)tracted correlation is a predetermined ma)imum and shifting the phase of pilot data by the estimated frequency offset.

2. A frequency offset compensating apparatus in an OFDM system, comprising:

   a correlating portion for demodulating input data by fast Fourier transformation, delaying a demodulated symbol by a predetermined period, and correlating a symbol demodulated during the delay to the delayed symbol;
   a pilot position detecting portion for comparing the correlation with a predetermined pilot position and e)tracting a correlation corresponding to the pilot position; and
   a frequency offset compensating portion for detecting the ma)imum of e)tracted correlations, estimating a frequency offset by comparing the ma)imum correlation and adjacent correlations with a predetermined threshold, and shifting the phase of pilot data by the estimated frequency offset.

3. The frequency offset compensating apparatus of claim 1 or 2, wherein the correlating portion comprises:

   a delay for delaying the demodulated symbol by the predetermined period; and
   a correlator for correlating the current demodulated symbol to the delayed symbol.

4. The frequency offset compensating apparatus of one of the claims 1 to 3, wherein the predetermined period is one symbol period.

5. The frequency offset compensating apparatus of one of the claims 1 to 4, wherein the pilot position detecting portion comprises:

   a pilot position shifter for storing pilot data transmitted by a transmitter and information about the positions of the pilot data and shifting the pilot data positions under predetermined control; and
   a pilot position detector for detecting a correlation among the outputs of the correlator according to a pilot position received from the pilot position shifter.

6. The frequency offset compensating apparatus of claim 1, wherein the frequency offset compensating portion comprises:

   an accumulator for accumulating the e)tracted correlation;
   a frequency offset estimator for estimating a ma)imum accumulated correlation to be the frequency offset if the accumulated correlation reaches a predetermined value; and
   a frequency offset compensator for shifting the phase of the pilot data according to the estimated frequency offset.

7. The frequency offset compensating apparatus of claim 1, wherein the frequency offset can be estimated up to

twice the number of sub-carriers.

8. The frequency offset compensating apparatus of claim 2, wherein the frequency offset compensating portion comprises:

an accumulator for accumulating the e)tracted correlation;
a frequency offset estimator for detecting the ma)imum of e)tracted correlations and estimating the frequency offset by comparing the ma)imum correlation and the adjacent correlations with the predetermined threshold; and
a frequency offset compensator for shifting the phase of pilot data by the estimated frequency offset.

9. The frequency offset compensating apparatus of claim 8, wherein the frequency offset estimator estimates the frequency offset by

$$\hat{f}_o - \hat{f}_o - 0.5,\ (C_{m\text{-}1} > C_{m+1} \text{ and } \frac{C_{m\text{-}1}}{C_{MAX}} > \mathit{THRESHOLD}$$

$$\hat{f}_o - \hat{f}_o + 0.5,\ (C_{m\text{-}1} < C_{m+1} \text{ and } \frac{C_{m+1}}{C_{MAX}} > \mathit{THRESHOLD}$$

$$\hat{f}_o - \hat{f}_o,\ (\text{all cases e)cept for } C_{m\text{-}1} > C_{m+1} \text{ and } \frac{C_{m\text{-}1}}{C_{MAX}} > \mathit{THRESHOLD},$$

$$\text{and } C_{m\text{-}1} < C_{m+1} \text{ and } \frac{C_{m\text{-}1}}{C_{MAX}} > \mathit{THRESHOLD} \qquad (7$$

where C_{MAX} is the ma)imum correlation and $\hat{f}_o$ is the estimated frequency offset.

10. The frequency offset compensating apparatus of claim 9, wherein the threshold THRESHOLD is 0.5.

11. The frequency offset compensating apparatus of claim 2, wherein the frequency offset estimation is performed after coarse frequency synchronization is acquired.

12. A frequency offset compensating method in an OFDM system, comprising the steps of:

demodulating input data by fast Fourier transformation, delaying a demodulated symbol by a predetermined period, and correlating a symbol demodulated during the delay to the delayed symbol;
comparing the correlation with a predetermined pilot position and e)tracting a correlation corresponding to the pilot position; and
estimating a frequency offset to the e)tracted correlation if the e)tracted correlation is a predetermined ma)imum and shifting the phase of pilot data by the estimated frequency offset.

13. A frequency offset compensating method in an OFDM system, comprising the steps of:

demodulating input data by fast Fourier transformation, delaying a demodulated symbol by a predetermined period, and correlating a symbol demodulated during the delay to the delayed symbol;
comparing the correlation with a predetermined pilot position and e)tracting a correlation corresponding to the pilot position; and
detecting the ma)imum of e)tracted correlations, estimating a frequency offset by comparing the ma)imum correlation and adjacent correlations with a predetermined threshold, and shifting the phase of pilot data by the estimated frequency offset.

14. The frequency offset compensating method of claim 12 or 13, wherein the correlation step comprises the steps of:

delaying the demodulated symbol by the predetermined period; and
correlating the current demodulated symbol to the delayed symbol.

15. The frequency offset compensating method of one of claims 12 to 14, wherein the predetermined period is one symbol period.

16. The frequency offset compensating method of one of claims 12 to 15, wherein the pilot position detection step comprises the steps of:

storing pilot data transmitted by a transmitter and information about the positions of the pilot data and shifting the pilot data positions under predetermined control; and
detecting a correlation corresponding to a pilot position shift among correlations.

17. The frequency offset compensating method of claim 12, wherein the frequency offset compensation step comprises the steps of:

accumulating the e)tracted correlation;
estimating a ma)imum accumulated correlation to be the frequency offset if the accumulated correlation reaches a predetermined value; and
shifting the phase of the pilot data according to the estimated frequency offset.

18. The frequency offset compensating method of claim 12, wherein the frequency offset can be estimated up to twice the number of sub-carriers.

19. The frequency offset compensating method of claim 13, wherein the frequency offset compensation step comprises the step of:

accumulating the e)tracted correlation;
detecting the ma)imum of e)tracted correlations and estimating the frequency offset by comparing the ma) imum correlation and the adjacent correlations with the predetermined threshold; and
shifting the phase of pilot data by the estimated frequency offset.

20. The frequency offset compensating method of claim 19, wherein the frequency offset estimator estimates the frequency offset by

$$\hat{f}_o - \hat{f}_o - 0.5,\ (C_{m-1} > C_{m+1} \text{ and } \frac{C_{m-1}}{C_{MAX}} > THRESHOLD$$

$$\hat{f}_o - \hat{f}_o + 0.5,\ (C_{m-1} < C_{m+1} \text{ and } \frac{C_{m+1}}{C_{MAX}} > THRESHOLD$$

$$\hat{f}_o - \hat{f}_o,\ (\text{all cases e)cept for } C_{m-1} > C_{m+1} \text{ and } \frac{C_{m-1}}{C_{MAX}} > THRESHOLD,$$

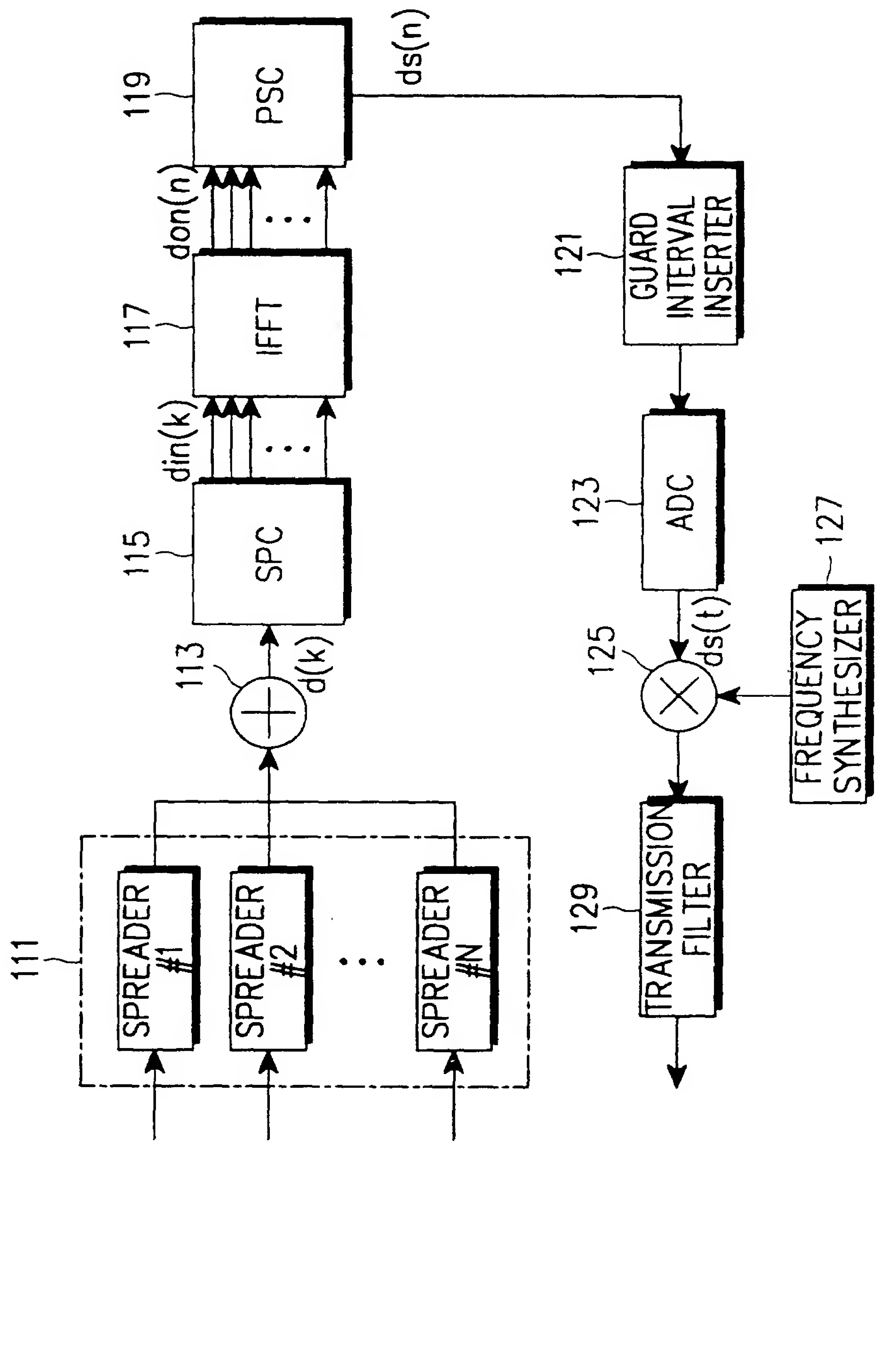
$$\text{and } C_{m-1} < C_{m+1} \text{ and } \frac{C_{m-1}}{C_{MAX}} > THRESHOLD \qquad (8$$

where C_{MAX} is the ma)imum correlation and $\hat{f}_o$ is the estimated frequency offset.

21. The frequency offset compensating method of claim 20, wherein the threshold THRESHOLD is 0.5.

22. The frequency offset compensating method of claim 13, wherein the frequency offset estimation is performed after coarse frequency synchronization is acquired.

FIG. 1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SPREADER #2
SPREADER #N
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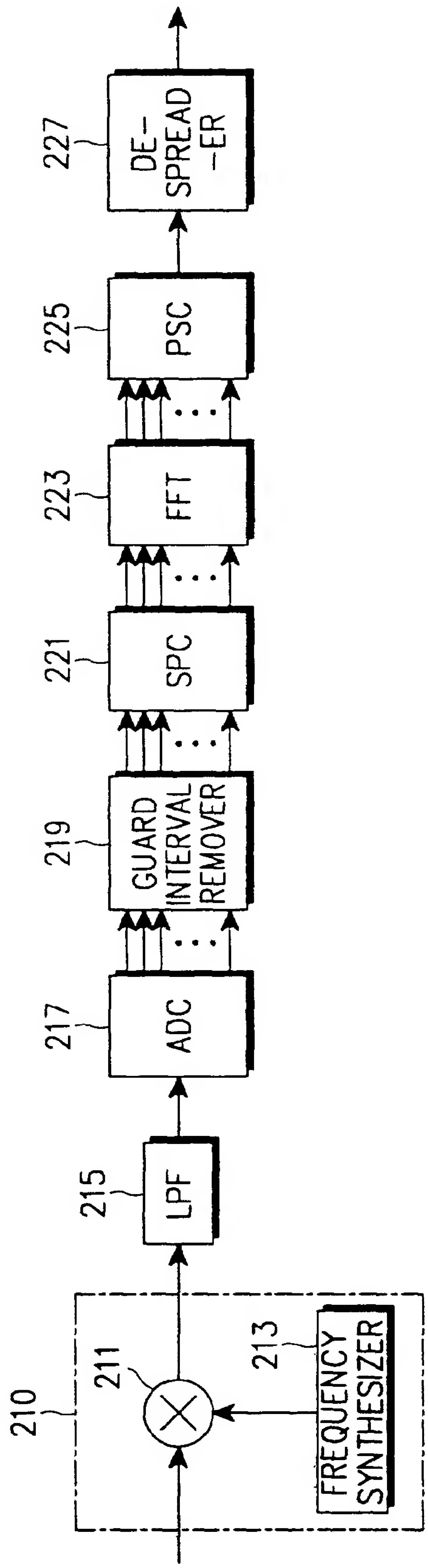
115
SPC
din(k)
117
IFFT
don(n)
119
PSC
ds(n)
121
GUARD INTERVAL INSERTER
123
ADC
125
ds(t)
127
FREQUENCY SYNTHESIZER
129
TRANSMISSION FILTER

FIG. 2



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FREQUENCY SYNTHESIZER
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ADC
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GUARD INTERVAL REMOVER
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FFT
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PSC
227
DE-SPREAD-ER

FIG. 3

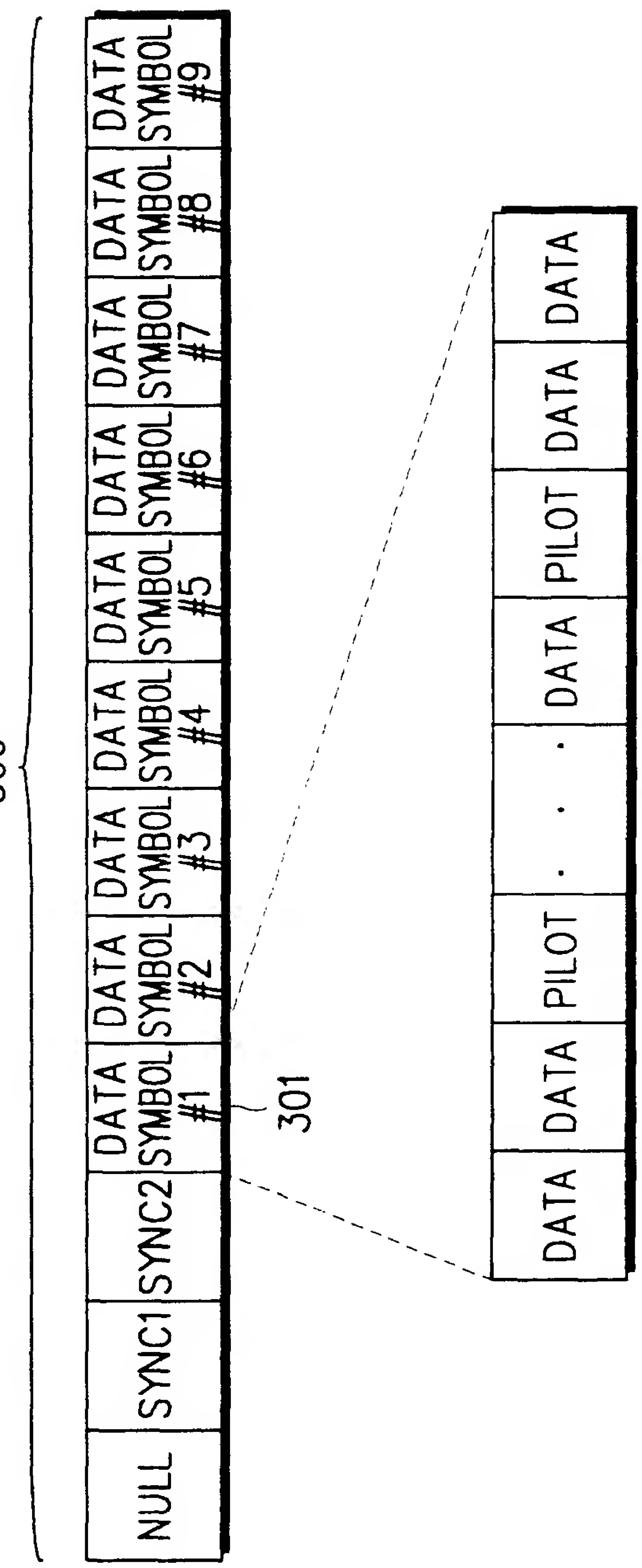
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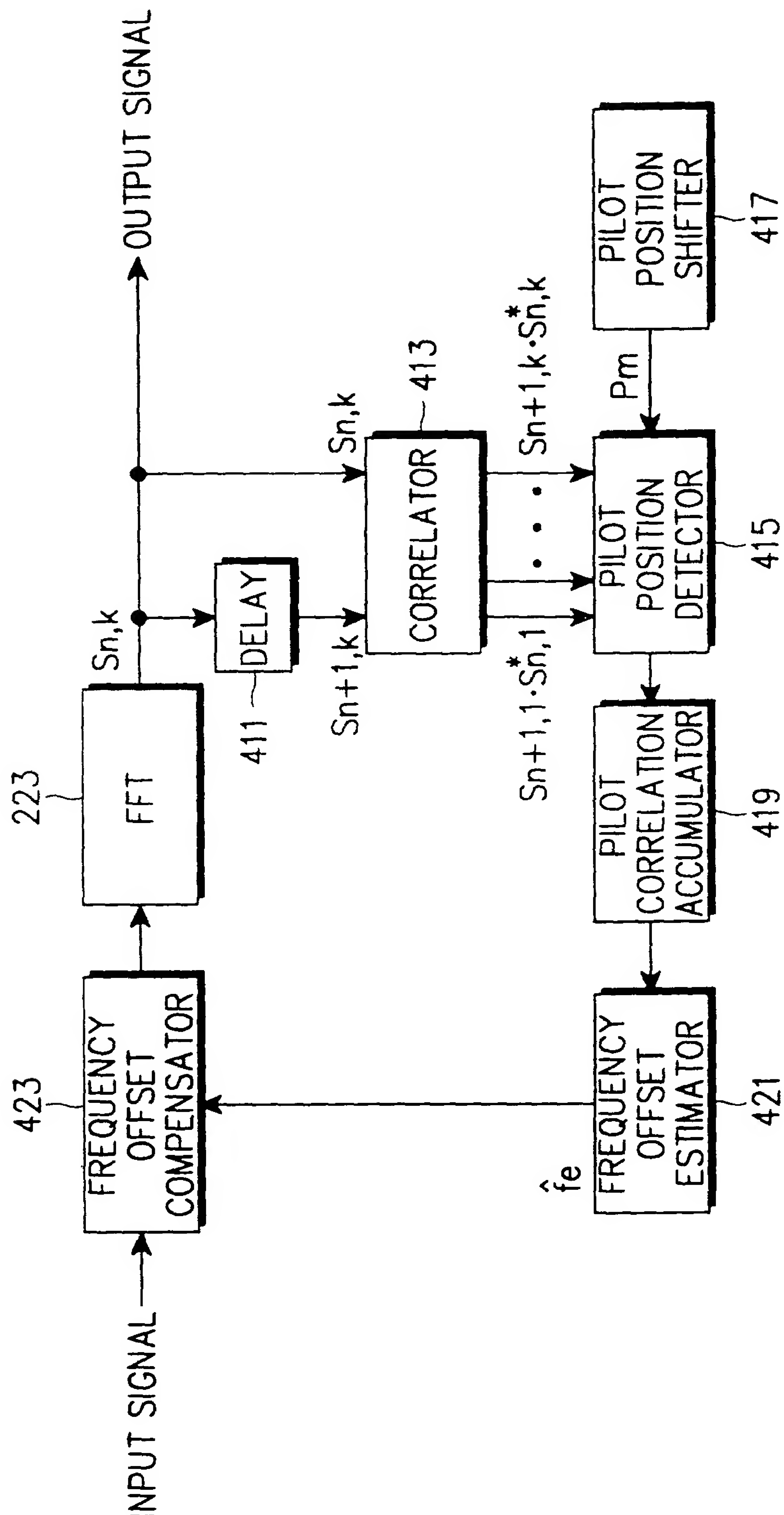
FIG. 4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Sn,k
DELAY
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Sn+1,k
CORRELATOR
413
OUTPUT SIGNAL
Sn+1,1·S*n,1
Sn+1,k·S*n,k
PILOT POSITION DETECTOR
415
Pm
PILOT POSITION SHIFTER
417
PILOT CORRELATION ACCUMULATOR
419
FREQUENCY OFFSET ESTIMATOR
421
f̂e

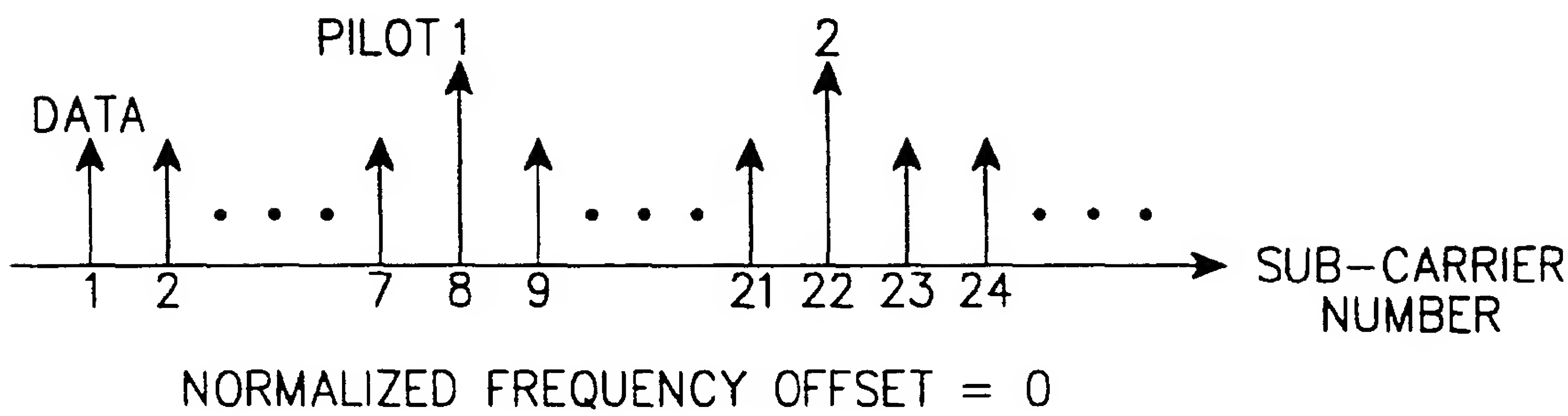
PILOT 1
2
DATA
1
2
7
8
9
21
22
23
24
SUB-CARRIER NUMBER
NORMALIZED FREQUENCY OFFSET = 0

FIG. 5A

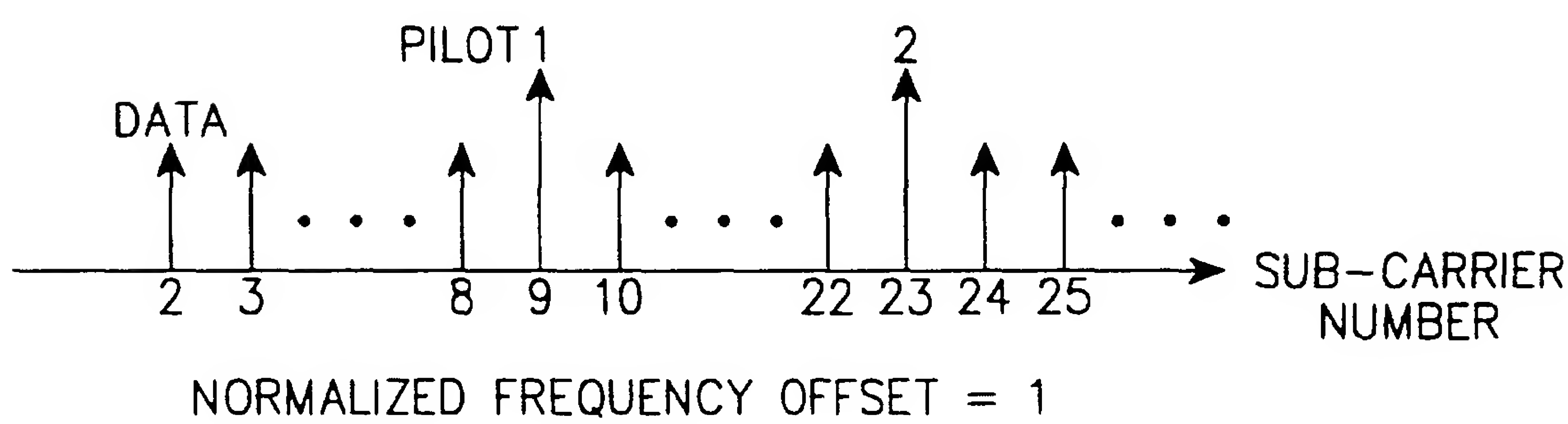
PILOT 1
2
DATA
2
3
8
9
10
22
23
24
25
SUB-CARRIER NUMBER
NORMALIZED FREQUENCY OFFSET = 1

FIG. 5B

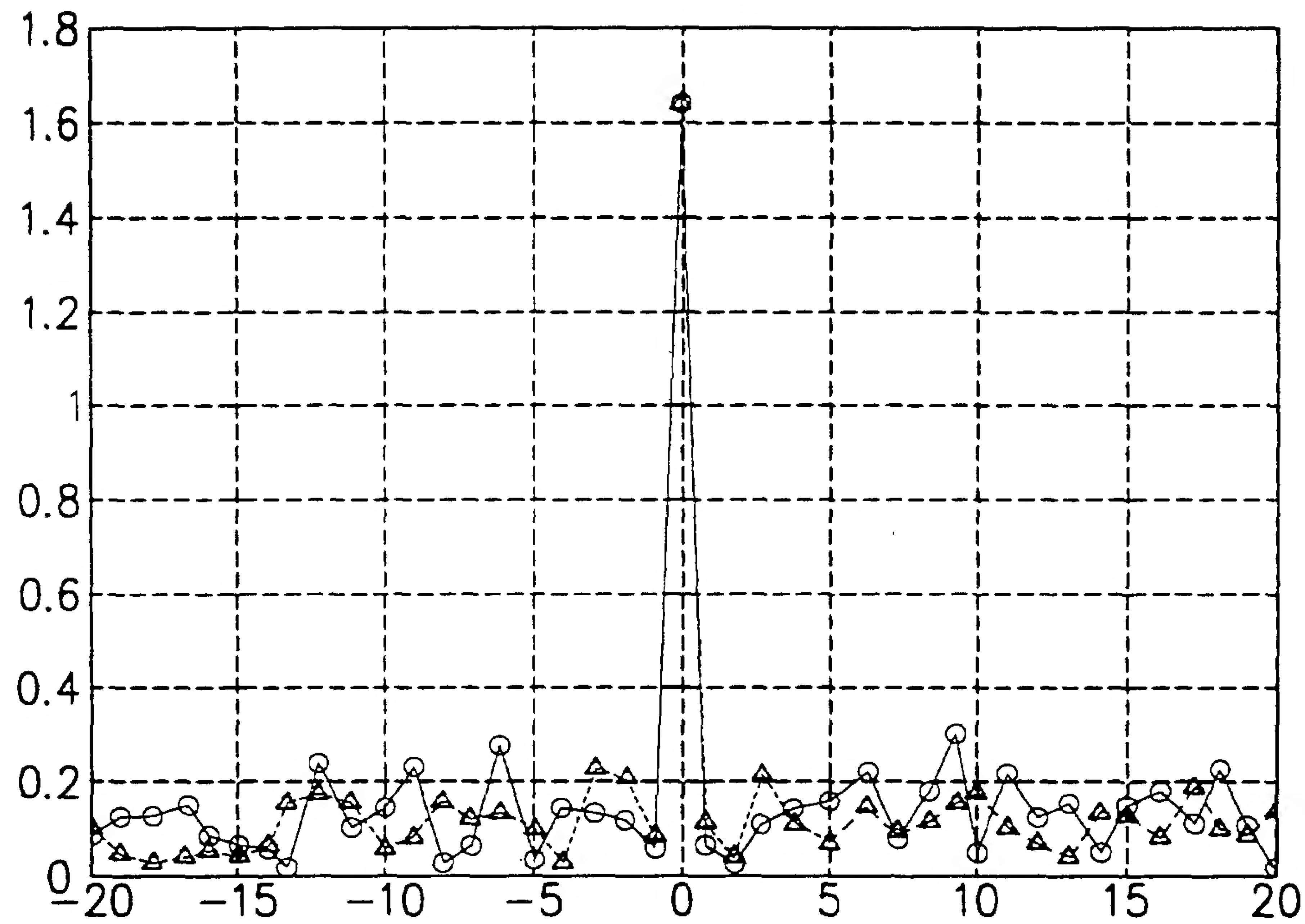

FIG. 6

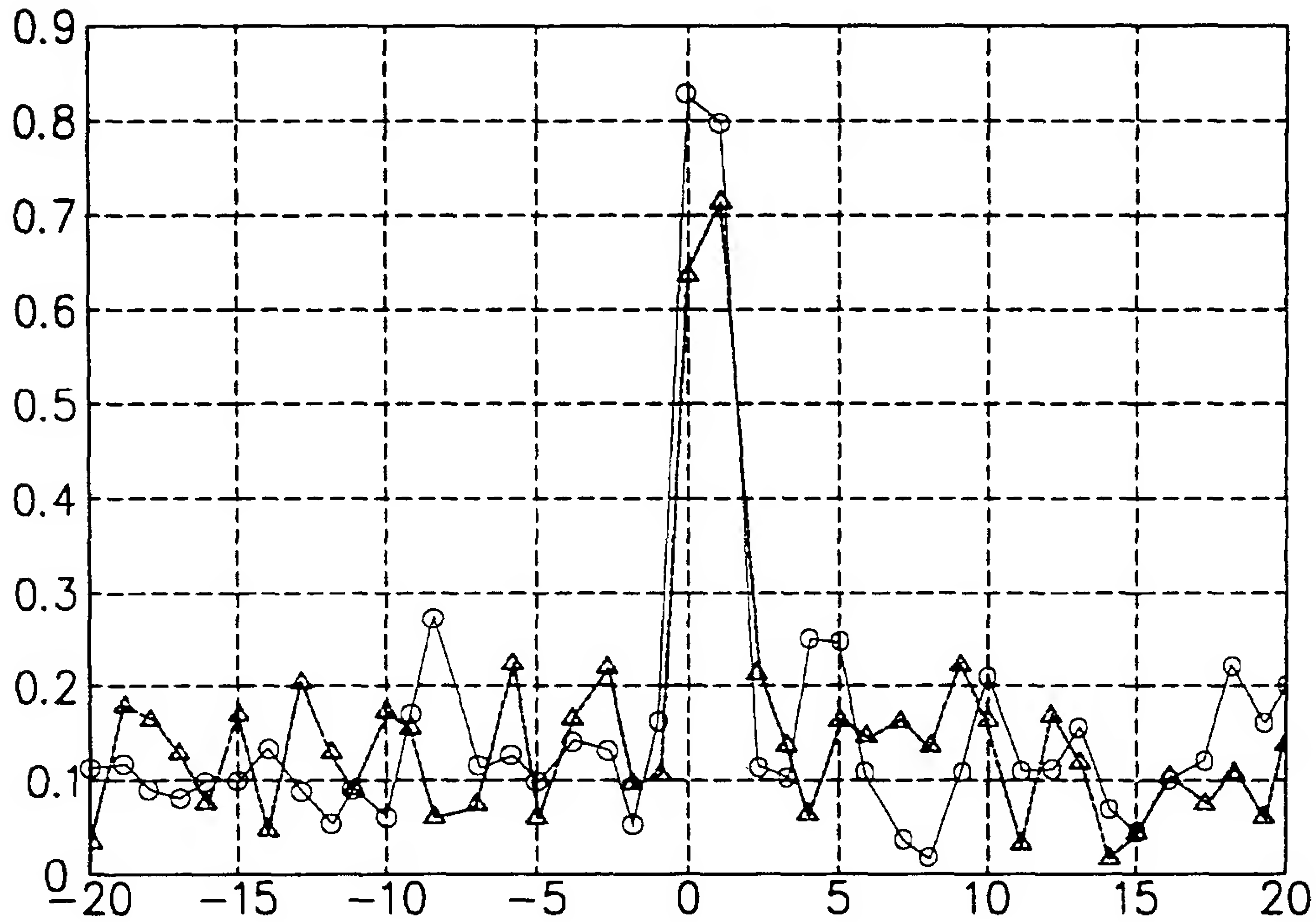

FIG. 7

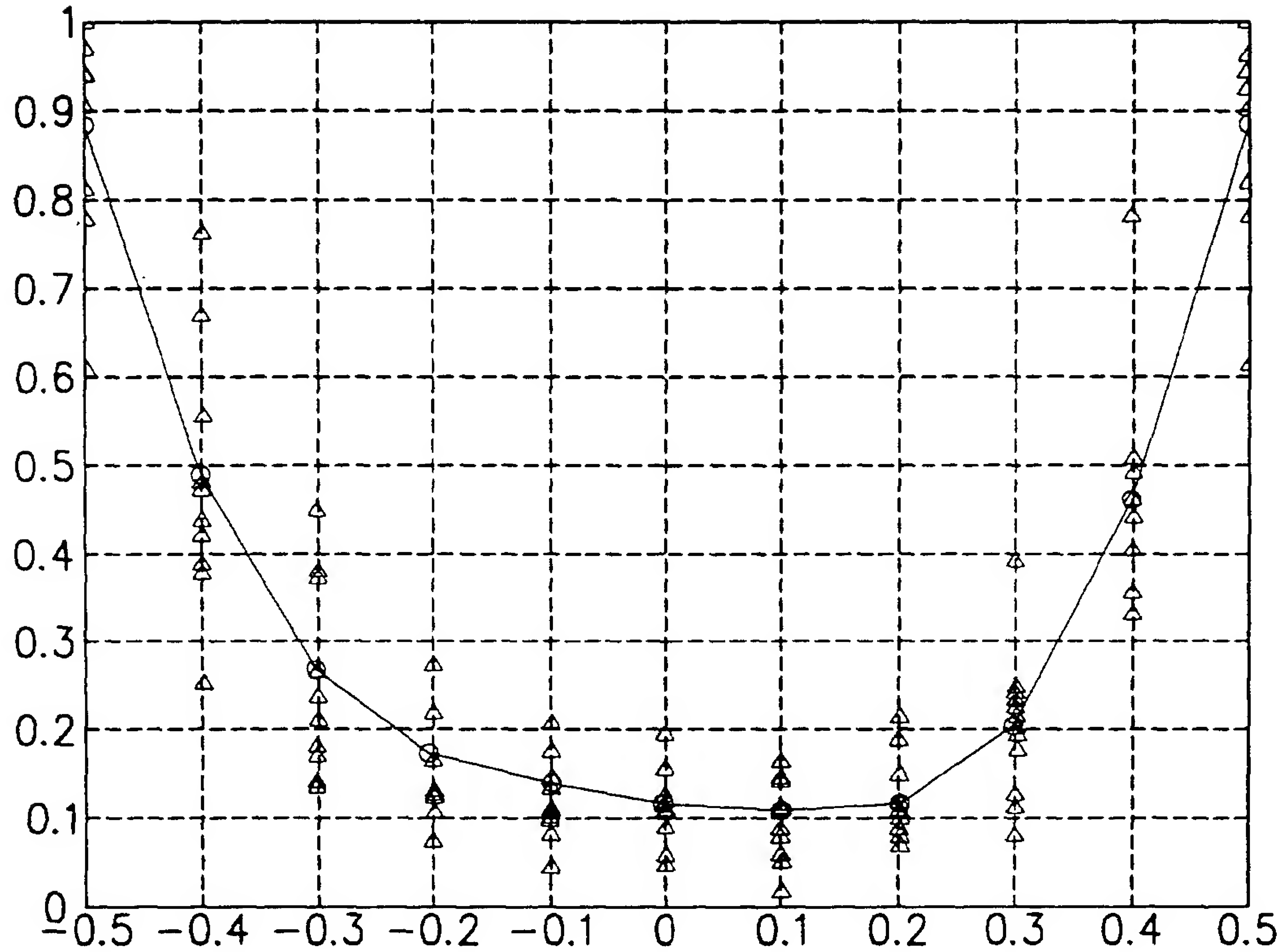

FIG. 8